X-ray Microtomography of Dense Granular Shear Flows

We have investigated the role of microstructure inside the granular shear zone using both a noninvasive x-ray microtomography technique at the Advanced Photon Source and magnetic resonance imaging. From x-ray tomography images, we calculated the local material packing fraction (the portion of space occupied by matter) for flowing mustard seeds, which exhibits oscillations on the single-grain length scale. These measurements, along with high-speed video, have made it possible to study the velocity and density profiles across shear bands for a wide range of materials and material parameters.

When forced to flow, granular materials, such as dry sand or cohesionless powders, develop localized shear bands in which relative particle motion is confined to thin domains, leaving adjacent areas basically static [1-5]. Shear bands, which also appear in situations where a lubricating fluid is restricted to ultrathin molecular layers [6], play a crucial role for many of the features of flowing material and thus have significant consequences for industrial and geophysical processes [7]. Because of the difficulty of viewing particle motion inside a three-dimensional (3D) granular medium, there is relatively little data about how the particles move within such a shear band. We have combined several noninvasive probes, magnetic resonance imaging (MRI), x-ray tomography, and high-speed-video particle tracking to investigate the behavior of the particle motion in such a situation. By using these tools, we have been able to obtain local information about the particle velocity, the particle rotation, and the packing density in a 3D Couette geometry. One surprising result from this data is that the shape of the particles, that is, the granular microstructure, plays an important role in establishing the velocity profile.

To probe the role of microstructure inside the narrow granular shear zone, independent determinations of the velocity and density profiles with spatial resolution well below the size of individual particles are required. Noninvasive measurements of this type so far have been limited to two-dimensional (2D) geometries in which optical tracking of all particle positions is straightforward [2,4,8-11] and to the surface of 3D systems [12]. However, recent advances in x-ray microtomography and MRI allow the noninvasive measurement of the density and velocity [13-15] in 3D granular flow. By combining these results with direct, high-speed-video particle tracking, we can also obtain information about the microscopic particle motion and rotation.

To sustain a uniform overall flow, we used a 3D Couette cell consisting of two vertical cylinders and a lower bounding surface. The gap between the cylinders was filled with a granular material, such as mustard seeds or glass spheres, and the inner cylinder was rotated at constant velocity while the outer cylinder was kept stationary. By gluing the granular material to the surface of both cylinders, the material near the inner wall was forced to move quickly, while the material near the outer wall was stationary.

To image the 3D system, we used x-ray microtomography [15,16]. The x-ray beam passed through the sample, which cast a shadow on a flourescent screen that was recorded by a 12-bit high-resolution camera. The 3D density information was reconstructed by using a suite of software developed and maintained by the GeoSoilEnviroCARS group at the Advanced Photon Source (APS). The high resolution of the reconstructed images was possible because of the very high x-ray flux at the APS. Imaging the Couette cell with a stationary inner cylinder yielded high-resolution images of the local density, as shown in Fig. 1a and Fig. 1b. In these images, the two cylindrical cell walls confining the material can be seen as the two bright rings, and the spherical mustard seeds are clearly visible. The 3D volumetric data set can be displayed in a number of different ways to visualize the packing of the material, such as by superimposing cylindrical cuts through the data on a computer-generated rendering of the Couette cell (Fig. 1c). By collecting full 3D volumetric data sets as the inner cylinder of the Couette cell was turned, x-ray imaging of particle motion inside the cell was possible. Such time-resolved microtomography is valuable for observing flow properties in a qualitative manner (see, for example, the movies at http://mrsec.uchicago.edu/granular). For determining particle velocities with high precision, high-speed

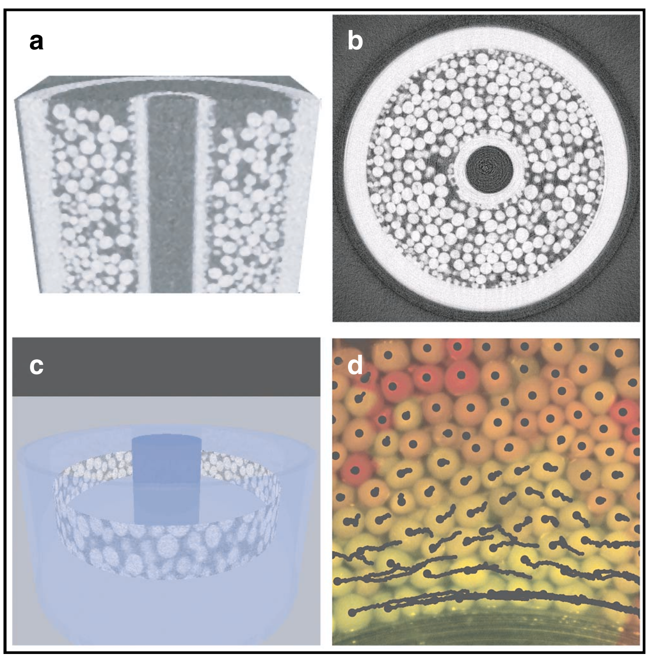

FIG. 1. Noninvasive x-ray tomography and high-speed video probes of granular Couette flow. (a) A volumetric cut through the reconstructed x-ray tomography data of the cell filled with mustard seeds. Both confining cylinders are visible. (b) An image of a horizontal slice through the cell. (c) A cylindrical cut through the volumetric data superimposed on computer rendering of the cell. (d) An image of the particles against the lower surface of the cell. The black lines show the particles' paths, and the colors correspond to the average velocity over the previous 200 ms.

video at the surfaces (Fig. 1d) and MRI spin-tagging in the cell interior offer advantages.

Using MRI spin-tagging, we measured the azimuthal velocity at each distance r from the inner cylinder wall. This velocity profile, v(r), decays sharply with r across the shear band (Fig. 2a) and becomes too small to measure at 6 particle diameters from the shearing wall (r = 0). On the lower surface of the cell, we used high-speed digital video to identify and track the motion of each particle (Fig. 1d). By comparing the motion of the particle centers with the overall flow of material given by the MRI experiments, we obtained the average rate and direction of particle spin (inset to Fig. 2a).

We calculated the local material packing fraction (the portion of space occupied by matter) from x-ray tomography images such as the one shown in Fig. 1b. The packing fraction profile, $\rho(r)$, for the flowing mustard seeds exhibits oscillations on the single-grain length scale (Fig. 2b). This partial layering of particles along the inner cylinder wall allows particle layers to slip past one another, giving rise to the sharp drops in v(r) seen in Fig. 2a.

The combination of three noninvasive techniques — x-ray tomography, MRI, and video — made it possible to study the velocity and density profiles across shear bands for a wide range of materials and material parameters (particle shape, polydispersity, and surface friction).

Quantitative analysis of data, as in Fig. 2, shows that there is a direct connection between the particle microstructure and the shape of the velocity and density profiles. For equal-sized spherical particles and very low interparticle friction, considerable layering is found, and the overall decay of the velocity profile in Fig. 2a is essentially exponential. However, for the more typical case of aspherical or frictional particles, layering is much weaker, and the velocity profile changes in character, switching from an exponential to a Gaussian centered on the shearing wall.

Noninvasive methods provide a new and powerful approach for probing the interior of sheared granular matter. The combination of tools that we have used here—x-ray tomography, MRI spin-tagging, and high-speed video—has been able to

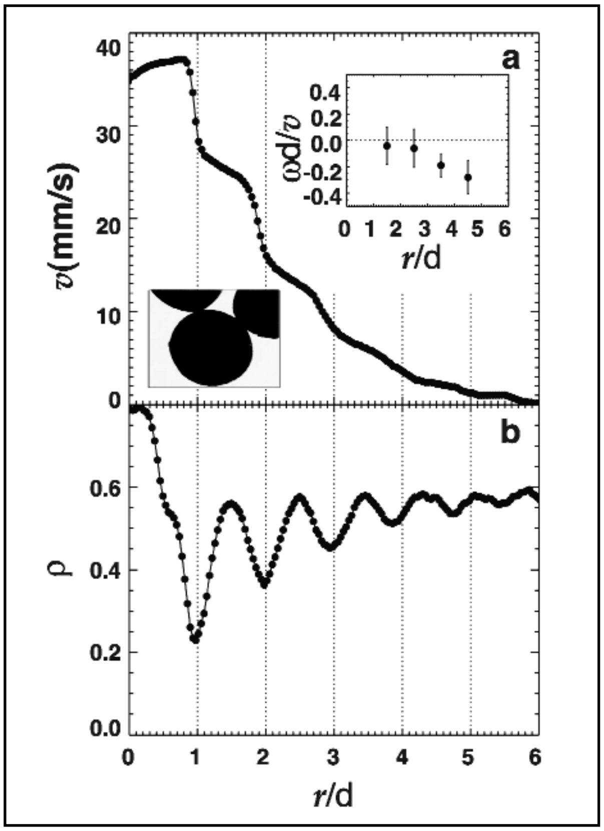

FIG. 2. Radial velocity, spin, and packing density profiles for spherical mustard seeds. (a) The average azimuthal velocity v(r) exhibits sharp drops in velocity at distances from the inner cell wall corresponding to integral particle diameters d. The inset shows the particle spin rate, determined by combining data from video, MRI, and x-ray tomography. (b) The density profile ρ(r) exhibits oscillations corresponding to layering of the material along the inner cylinder wall. This layering gives rise to the sharp drops in velocity seen in v(r).

provide data that heretofore were unattainable by conventional techniques. The data contain surprises, such as the role of microstructure for the flow profiles. The data also provide some of the most relevant information needed to construct a theory for such motion: density, velocity profiles, and fluctuations. Data of this kind will provide a benchmark for theoretical attempts at developing a coarse-grained set of equations (such as the Navier-Stokes equation in fluids) to describe flowing granular material.

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